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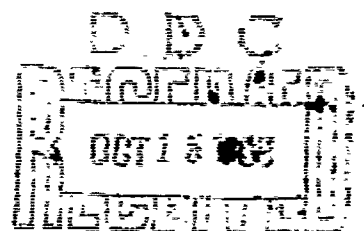
**SYNOPSIS OF A THUNDERSTORM RESEARCH
PROGRAM (ROUGH RIDER) FOR 1966-1967**

EDWARD MILLER

Capt, USAF

TECHNICAL REPORT ASD-TR-68-29

AUGUST 1968



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**DIRECTORATE OF FLIGHT TEST
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

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SYNOPSIS OF A THUNDERSTORM RESEARCH PROGRAM (ROUGH RIDER) FOR 1966-1967

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FOREWORD

This report documents the final two years (1966 and 1967) of a Government sponsored research program which was designed to gather meteorological data on thunderstorms during mid-April to mid-June of the respective years. An additional data gathering period was also accomplished during August of 1966.

This program functioned under the official nickname "Roughrider Six" during 1966 and "HAVE Roughrider" during 1967. The system, and task numbers for 1966 were 804A, 8620, and 606 respectively. These same numbers were changed to 921K, 97340, and 601 for 1967.

The governmental participants included the Air Force Systems Command (AFSC), the Air Force Cambridge Research Laboratory (AFCRL), the Air Force Weapons Laboratory (AFWL), the National Severe Storms Laboratory (NSSL), and the Federal Aviation Administration (FAA). The nongovernmental organizations which took part in the effort were the Sandia Corporation and the Lightning and Transients Research Institute which were contracted by the AFWL and the FAA, respectively, to aid in a particular phase of the project. The project supervisory officials were Dr. Robert M. Cunningham, Cloud Physics Branch, Meteorology Laboratory, AFCRL; Dr. Edwin Kessler, Director, NSSL; Major Robert J. Vanden-Heuvel, Task Force Commander and Project Pilot (1966), Aeronautical Systems Division (ASD); and, Major Nathaniel O. DeVoll, Task Force Commander and Project Pilot (1967), ASD.

This report was written by Captain Edward Miller, Project Engineer, ASD, and released for publication during May 1968.

This report has been reviewed and is approved.


RICHARD O. RANSBOTTOM
Colonel, USAF
Director of Flight Test

ABSTRACT

The ultimate objective of the meteorologists involved in this particular study of the cumulonimbus was to obtain sufficient data during various stages of the cycling thunderstorm to produce a detailed model of the subject and thus improve the ability to predict the magnitude and, where applicable, the direction of the variables involved. This project required a platform from which instrumentation could be utilized to sample the sought after storm information. The platform was an instrumented AF F-100F aircraft which was used to penetrate thunderstorms and the air space surrounding the perimeter of the storm. The aircraft was vectored by ground radar into the particular areas of interest to record the various data. This information would be analyzed with data recorded simultaneously by ground-based meteorological equipment to provide a relatively detailed, time-correlated picture of the synoptic situation. Needless to say, the data acquired is voluminous in quantity and at the time of this writing is in the preliminary stages of analysis. Therefore, this report will not delve into a detailed discussion of the data but shall note from whom such an analysis can eventually be obtained.

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SYMBOLS

α	angle of attack, radians
α_0	angle of attack at start of penetration, radians
c	mean geometric wing chord, feet
g	acceleration due to gravity, feet/second squared
H	Constant, grams inches squared Rankine degree/pound meter cubed
K_g	Gust factor, dimensionless
K	Recovery factor, dimensionless
l	distance between angle of attack vane and the pitch rate gyro, feet
M	Mach number, dimensionless
m	mass, slugs
\ddot{n}	normal acceleration, feet/second squared
\bar{n}	average normal acceleration for the penetration, feet/second squared
Δn	nondimensional normal acceleration increment
P	pressure, pounds/square inch
R	gas constant, foot pound force/pound mass Rankine degree
S	wing surface area, square feet
T_{ic}	total temperature, degrees Rankine
T	static temperature, degrees Rankine
t	time, seconds
U_{DE}	derived gust velocity, feet/second
V_g	gust velocity, feet/second
V_e	equivalent airspeed, feet/second
V_i	instantaneous airspeed, feet/second
V	volume of the gas, cubic feet
W	aircraft weight, pounds

SYMBOLS (CONTD)

w	water vapor content per unit volume of dry air, grams/cubic meter
w'	absolute humidity of the gas-line sample transferred to atmospheric conditions, grams/cubic meter
μg	aircraft mass ratio
$\frac{d C_L}{d \alpha}$	slope of the lift curve
ρ_0	air density at sea level, slugs/cubic foot
ρ	air density, slugs/cubic foot
θ	pitch angle, radians
$\bar{\theta}$	average pitch angle, radians
$\dot{\theta}$	pitch rate, radians/second
$\bar{\dot{\theta}}$	average pitch rate, radians/second

SUBSCRIPTS

ATM	atmosphere
SAM	sample
GL	gas line
a	dry air
w	water vapor
i	instantaneous
MAX	maximum
0	zero

SECTION I

INTRODUCTION

1. The NSSL of the Environmental Science Services Administration conduct an intensive research program to accumulate data on the winds, rain, hail, snow, turbulence, and icing characteristics of the cumulonimbus with the objective an ability to predict using radar the degree of severity and location of these elements within the storm by ground analysis of the storm. A simultaneous research effort was being conducted by the AFCRL with the resultant goal that of a detailed understanding of the electrical phenomena associated with the thunderstorm. The Aeronautical Systems Division provided these organizations with support personnel and an instrumented F-100F aircraft for internal probing of the thunderstorms to gather the essential data. Separate flight phases (Phases I and II) were programmed to obtain this data because the NSSL program (Phase I) required an elaborate array of ground support personnel, equipment, and facilities, all of which could readily be found only within a 100 nautical mile radius of the NSSL (Norman, Oklahoma), although the probability of recording the electrical data requested by the AFCRL in storms which formed over this area was relatively low. Therefore, the supporting flights for the AFCRL (Phase II) effort were based at Patrick AFB, Florida, because of the relatively large amount of electrical activity in the storms as well as the availability of ground support facilities.

SECTION II

TEST INSTRUMENTATION AND PURPOSE

2. The primary test instrument was the F-100F aircraft (Figures 1 and 2). The aircraft's noseboom was all that was structurally strengthened for the penetrations although some prototype equipment was installed to protect the aircraft and pilot from lightning strikes (Reference paragraph 77 of this report). The aircraft functioned as a test instrument since its attitude and movement were recorded and this data was utilized to determine the magnitude of the gust loads encountered.

3. Most of the test instrumentation carried in the F-100F was used during both the 1966 and 1967 programs. This instrumentation can be divided into three groups. Group I refers to equipment used during all phases; Groups II and III equipment were used during Phase I (1966 and 1967) and Phase II (1966) respectively. The equipment for each group was as follows:

Group I

Angle-of-attach indicator	Fuel weight indicator
Normal accelerometer	Time-lapse camera
Pitch and roll gyros	Voice recording
Pitch and roll rate gyros	Nitrogen purge system
Airspeed and altitude transducers	Diverter dischargers
Temperature probe	Static dischargers
Ice Detector	Canopy protector strip
Magnetic heading indicator	Time code generator
TACAN bearing & range indicator	Continuous ignition capability
Differential static pressure indicator	Leach Magnetic Tape System
Elevator & aileron position indicators	

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GROUP II

Hail probes
APN-91 receiver-transmitter
1680 mc beacons
Angle-of-sideslip indicator
Pilot stick force indicator
Dropsondes
Lateral & longitudinal accelerometers
Yaw angle indicator
Rudder position indicator
Yaw rate gyro
VGH recorder

GROUP III

16mm time-lapse cameras
Current shunts & probes
Electric field mills
Instrumented wing tank
Pressure transducer
Range time receiver

4. The following discussion pertains to those instruments which require further explanation as to their use on this project.

HAIL PROBES

5. A pair of prototype instruments were designed to give an indication of the mass of some of the hail encountered and were mounted above the upper lip of the inlet duct. Each probe was a cantilever beam designed so that in a majority of cases, the output of either probe would indicate a mass less than the actual mass of the hail because any compression or torsion of the probe was not recorded. The probe output was emitted from strain gages positioned to pick up only probe "bending" in the XY plane (Figure 3). The components of torsion and compression were considered negligible.

STATIC PRESSURE VARIATION

6. The Rosemount Engineering Company pressure measurement system model 800F7A was used to detect variations in the atmospheric static pressure in the thunderstorm cells. This instrument was composed of a pressure sensor and an altitude reference controller. The device had two phases which were referred to as the standby phase and the "operate" phase. During the standby phase, the resultant output of the system was zero. When the operate phase was selected, the instrument would compare instantaneous static pressures encountered during the penetration with the initial static pressure sensed

at the start of the operate phase. Accuracy of the system is $\pm 3\%$ of full scale under all conditions (Reference 1). Therefore, the maximum error in the instrument under the conditions encountered should be ± 60 feet.

INFRARED THERMOMETER

7. Temperature of the encountered environment was determined by an infrared device mounted on the left side of the aircraft. The centerline of the instrument's 3-degree field of view was perpendicular to the aircraft centerline and laid in a horizontal plane.

8. The infrared thermometer consisted of a sensing head and an electronics console. The sensing head held the blackbody source, spectral filter, thermistor bolometer detector, motor driven chopper, and a preamplifier. The console housed the power supply, post amplifier, and rectifier among other electronic components. The central part of the system was the insulated blackbody source, the front of which was sealed by a spectral filter and the rear with the thermistor bolometer detector. A thermistor washer and heater were used to keep the reference cavity, spectral filter, and detector at a constant temperature (40°C).

9. The method of operation was for electromagnetic radiation between 8 and 13 microns to pass through the filter and hit the detector. This influx of radiation was interrupted by a multivane chopper operated at 90 cycles per second. During these interruptions, the detector would receive an input from the temperature-controlled reference cavity. The system would compare the radiation from the controlled source with that received from the target. A resultant AC signal proportional to the infrared differential was then emitted by the electronics console and recorded. The accuracy of the instrument is quoted (Reference 2) as $\pm 8^{\circ}\text{F}$ under the conditions to which it was subjected.

TIME-LAPSE CAMERA

10. A Flight Research 16mm camera was mounted directly in front of the pilot (Figure 4) during the 1966 phases. The camera had a 10mm, f 1.8 Angenieux lens with a fixed focus, a horizontal viewing angle of 55.4 degrees, and a vertical viewing angle of 41.1 degrees. The unit was set at an f stop between 5.6 and 8.0 for the Kodachrome II film. Film was exposed at the rate of one frame per second.

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11. A 35mm camera was utilized during 1967 in place of the 16mm time-lapse camera. The 35mm camera (Figure 5) operated at a frame a second and was set at F-11 and focused on infinity. Ektachrome film was used.

AN/APN-91 RECEIVER-TRANSMITTER

12. The radio beacon used is a subminiaturized airborne transponder designed for operation in the S frequency band. The unit is composed of a power supply, bandpass filter, and a receiver-transmitter. When interconnected to a receiving antenna and a transmitting antenna, the equipment transmits a coded reply in response to each signal pulse interrogation received from a ground or airborne radar set. The coded reply pulses, when viewed on the interrogating radar indicator as beacon images, permit radar tracking of the radio beacon equipped aircraft at far greater distances than obtained by skin reflections.

13. The instrument is capable of transmitting any of six reply codes. The desired code was chosen before flight. A decoder was built into the beacon so that only a radar set interrogating with the correct pulse sequence would be answered.

1680 MEGACYCLE BEACONS

14. Two radio-ode transmitters were installed on the aircraft. One beacon was mounted under the canopy while the second was placed to protrude from the underside of the fuselage. Both of these units were tracked with ground receivers. The resultant data from the transmitters gave the penetration aircraft elevation and azimuth angle.

ELECTRIC FIELD MEASUREMENT

15. The AFCRL provided all the instrumentation pickups aboard the F-100F aircraft used to measure lateral and vertical components of the electric fields encountered during the traverses. This instrumentation included a three-channel solid-state computer, three field mills, and various other transistorized components. No attempt will be made to describe the equipment since it was maintained and its data output interpreted by AFCRL.

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DROPSONDES

16. The dropsondes (Figure 6) utilized were designed for release from high speed aircraft into various degrees of thunderstorm turbulence. The telemetry data was monitored at three separate ground stations and the sondes were tracked via radar to obtain data on the wind vectors encountered.

17. The subject dropsondes were procured and maintained by NSSL personnel and any detailed information on the data or operation of these units can be obtained from the NSSL.

VGH RECORDER

18. The NASA VGH recorder was utilized as an independent system for the sensing and recording of the airspeed, altitude, and acceleration envelopes flown during the various flight profiles. These recordings were used to provide an aid in the data analysis and to provide a simplified means for quickly scanning the data.

19. The recorder system is composed of a small electronics package, an accelerometer, and a film magazine. The electronics package contains the airspeed and altitude transducers as well as the light source and the galvanometers for the light-sensitive recording paper. The magazine held 200 feet of film paper and at a running speed of 0.125 inch per second permitted a recording time of 320 minutes. The electronics and the magazine section were installed under the nose cowl while the accelerometer unit was mounted aft of the rear cockpit.

20. The original paper records accumulated during the flight phase are filed with the NSSL. Any detailed analysis performed and the correlation of these records and those of the primary recording system will be accomplished by the NSSL.

MAGNETIC TAPE SYSTEM

21. The MTR-3200 magnetic tape recorder manufactured by Leach Corporation was the primary source for recording data during all phases (Figure 4). Of the total number of channels available on this recorder, four were used as analog

channels with an average of seven variables per channel while eight other channels were utilized as FM carriers. The recorder speed of 3.75 inches per second was chosen to ensure ample recording time for the entire flight.

LIGHTNING STUDY INSTRUMENTATION

22. This instrumentation package which was used only during Phase II (1966) was composed of two independent subsystems. The primary subsystem was composed of aluminum probes, current shunts, oscilloscopes, and 35mm cameras. This subsystem was designed to permanently record current versus time relationships for each lightning strike on the various aircraft extremities.

23. Aluminum probes were mounted on each wingtip (Figure 7) and the vertical stabilizer (Figure 8) to provide relatively vulnerable targets for any strikes near these sections. The probes were, in turn, connected to 0.005-ohm-current shunts which were grounded to the aircraft so that any current flow through the probes would be channeled through the shunts then back to the aircraft to follow the normal current flow path. An oscilloscope was attached to each shunt to measure the voltage differential across the shunt. This differential was shown on the calibrated scope grid screen as a current versus time relationship. A 35mm camera was focused on the screen of each scope to achieve the permanent documentation required. Four 35mm cameras and four oscilloscopes were used, one scope and one camera for each current shunt. These items were all housed in a 450-gallon tank hung on the left wing (Figure 9).

24. The noseboom was altered to serve as the fourth aluminum probe by bisecting the boom and inserting a current shunt. This section was then covered by laminated fiberglass. An outer fiberglass casing was installed around this wrapping to strengthen the boom (Figure 10). The fourth oscilloscope mentioned previously was attached to this shunt.

25. The second subsystem, which consisted of four cameras, was designed to document any electrical phenomena on the aircraft noseboom, wingtips, fuselage, and/or empennage. One camera was mounted under the steel-capped ILS antenna in the upper lip of the inlet duct (Figure 10), and another camera was installed between the cockpits (Figure 11). Both of these Flight Research

cameras carried 16mm Kodachrome II Daylight film with the additional feature of being shutterless so as to provide exposed film during the entire mission. The film in each camera moved at a rate of a frame a second. The camera focused on the noseboom was set at f 11 while the other camera, set at f 16, encompassed the wingtips and tail section in one frame by the use of a wide-angle lense. The third camera was 16mm and was housed in the 450-gallon tank (Figure 12). It was focused on the right wingtip and set at f 22. The fourth camera was 35mm with a 180-degree lense focused to include a complete side view of the aircraft. This camera was also mounted in the wing tank (Figure 12).

COCKPIT CONTROLS

26. All test instruments were controlled from test switches on the center and right consoles (Figures 13 and 14) in the front cockpit except for the tape system run-stop switch which was connected to the radar reject button on the pilot's stick. In addition, the stick trigger was altered to provide the pilot with the capability of putting event markings on particular sections of the magnetic tape record.

HYGROMETER

27. The hygrometer consists of two physically separate units, a sensor and a control unit (Figure 15). A mounting block for the sensor (Figure 16), interconnecting tubing between the source of the gas sample and the sensor (Figure 17), a calibration platinum resistor unit (Figure 18), and an extended section of coaxial cable between the sensor and the electronics were added to the system for this installation.

28. The sensor consists of a thermoelectric cooler, mirror-light system, and a platinum resistance thermometer. Basically, the sensor functions as follows: The cold junction of the thermoelectric cooler is a stainless steel mirror in which the platinum resistance thermometer is imbedded. The mirror which is exposed to the sample gas, reflects light from a source onto a photodiode. The resultant condensate on the mirror surface due to cooling of the mirror to the dew-point temperature of the gas sample causes refraction of the light from the mirror to the photodiode which, in turn, stops the decrease in surface temperature of the cold junction. The platinum resistance thermometer in the mirror monitors this dew-point temperature.

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29. The control unit contains the control circuitry and power supply for the sensor and provides millivolt output signals proportional to the dew-point temperature.

30. The calibration platinum resistor was placed in parallel electrically with the sensor. A toggle switch mounted in the front cockpit enabled the pilot to provide a known input to the hygrometer system from the calibration unit.

31. The gas sample was taken from the engine at a point between the low and high pressure compressors. The tap-in port was flush-mounted and the tubing was stainless steel of 0.19-inch inside diameter. The part of the tubing which would be inaccessible when the engine was installed in the aircraft was provided with a vacuum jacket to preclude the chance of condensation occurring in this section of tubing.

SECTION III

TEST PROCEDURE

32. The Phase I flight activities were based on the NSSL radar studies of thunderstorm systems within the Roughrider range of operations. These studies required daily effort by the NSSL personnel to enable them to brief the pilots and engineer each morning concerning a tentative takeoff time for the ASD aircraft. The ground activity for the Phase II flights followed a similar procedure. That procedure was for the Task Force Commander and the Project Supervisor to decide upon a tentative takeoff time based on the daily study of the Patrick AFB weather reports and radar pictures. These procedures resulted in a total of 55 flights over the two test sites and an accumulation of approximately 1,304 minutes of recorded data (Table I).

33. The radar system was not only the prime instrument used in planning but also in the actual flight operations. This system established two criteria which had to be met before a storm would be considered for study. The first of these criteria was for the storm to be positioned within 100 nautical miles of Norman, Oklahoma, for Phase I, or 200 nautical miles of Patrick AFB, Florida, for Phase II. The variation in radii was due to the variation in maximum range of the radar systems used. The second qualification was for that part of the storm to be penetrated to have a radar reflectivity value equal to or less than $10^5 \text{ mm}^6/\text{m}^3$. This value is proportional to the echo power received by the radar system and is also dependent on the nature and size of the storm particles encountered. Experience has shown that the probability of encountering hail which would damage the F-100F aircraft is greatly magnified when the reflectivity level goes above the quoted value. Experience has shown that compliance with this second criterion was not necessary for flights over the Florida test area.

34. All the Roughrider aircraft were vectored to the subject storm system by an FAA radar controller. However, similarity of flight operations ceased upon reaching the storm cells. Therefore, each test procedure is considered separately in the following paragraphs.

F-100F AIRCRAFT

35. This aircraft was given the proper penetration heading and altitude by the radar controller. The pilot's objective was to hold this heading as well as his aircraft's attitude. The prescribed penetration speed was termed to be 275 KIAS. During the penetration, the pilot was requested to verbally describe his experiences which would in turn be recorded on tape. This procedure was repeated as many times as feasible per mission, and was the flight procedure adopted during all storm penetrations with this aircraft.

36. The F-100F, Phase I (1966 and 1967) flight activity included a plan to release dropsondes in the penetrated storm cells. The aircraft was tracked via the 1680 mc beacons until the time of dropsonde release. At this time, the beacons were turned off and the released dropsondes began emitting a 1680 mc signal after release from the aircraft. The F-100F aircraft was to exit the storm cell and remain in a holding pattern until the dropsonde had fallen through the cell. Then the penetrations were to continue. The dropsonde flights were not flown over the Florida test area.

37. Phase II F-100F aircraft flight operations included not only the penetration procedure listed in the former paragraph but also included an attempt to record cloud-to-ground lightning as it struck the aircraft. Such an attempt was independent of the penetration mission although both missions were coordinated in one flight. A brief explanation of the procedure for inducing a lightning strike is given here because such an explanation, in turn, serves to describe the flight operations:

a. Basic theory indicates that when the distance between two points of potential difference is reduced, the probability of electrical discharge between the points is increased. Placing a conducting object into this gap greatly enhances the possibility of this object's being used as a segment of the discharge path between the points. Based on this belief, it was planned to fire rockets trailing wire from sea level toward the base of a thunderstorm and to time the firing so that the F-100F aircraft was over the rocket when it attained its peak altitude. Any discharge between the storm and the rocket could be monitored by ground equipment electrically connected to the rocket by the wire. The aircraft test instrumentation would also record data should the strike hit or pass near the aircraft.

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b. One rocket firing facility was set up in central Florida and utilized a series of three 81mm mortar tubes to fire the rockets. The second firing facility was based on board the LTRI research vessel "Thunderbolt" (Figure 19). Aside from a number of preparatory missions, there were no flights over these facilities because the storms that did accumulate did not attain the prerequisites necessary for possible accomplishment of the mission. This should not be interpreted to mean the procedure used to induce the cloud-to-ground strikes does not work. In fact, the LTRI succeeded in inducing 17 such strikes out of 23 attempts (Reference 3).

T-33 AIRCRAFT

38. The T-33 aircraft was used in both phases solely as a safety measure. This aircraft had the task of rendering all assistance possible to the F-100F should the aircraft run into problems. The chase aircraft, as the T-33 was called, would hold or orbit in an area specified by the FAA radar controller during each mission. This aircraft was chosen for its role because it was the most suitable jet aircraft available.

SECTION IV

DISCUSSION (PHASE I)

39. The data accumulated during Phase I as a result of the F-100F penetrations included: (a) the data presented in Table II; (b) a quantitative and qualitative measure of the storm erosion conditions; (c) a feasibility study concerning the release of radiosondes from high speed aircraft; and (d) a study to decide the feasibility of using a dew-point sensor to measure the combined quantity of liquid and solid water in the thunderstorm.

MAGNETIC TAPE DATA

40. All data necessary to directly or indirectly obtain values for the parameters in Table II, aside from the cloud formation film and the erosion intensity data, is recorded on magnetic tape. The values of the vertical gust velocity, derived gust velocity, and ambient temperature were the only parameters which could not be read directly from the tapes but were calculated using the respective mathematical relationships presented in the following paragraphs.

41. The vertical component of the gust velocity was the only component calculated at the time of the writing of this report primarily because it has significantly greater peak magnitudes relative to the other two vectors. The procedure utilized to obtain a time history of this vertical component was to measure the undisturbed flow angle relative to the aircraft and to correct this value for the effects of aircraft motion. The equation used to combine these variables to calculate the vertical component of the gust velocity was:

$$V_g = V_i (\alpha_i - \alpha_0) - V_i \int_0^{t_i} (\dot{\theta}_i - \bar{\theta}) dt + \ell (\dot{\theta}_i - \bar{\theta}) + \int_0^{t_i} (\dot{n}_i - \bar{n}) dt \quad (1)$$

One of the obvious assumptions in the equation is that the particular angles involved are small enough to permit replacement of the sine of the angle by the value of the angle in radians. The other assumptions made as well as a detailed analysis of this equation can be found in Reference 4.

42. The equation used to obtain values of the derived gust velocity is stated as follows (Reference 5):

$$U_{DE} = \frac{2 \Delta n_{max} W}{\frac{dC_L}{d\alpha} \rho_0 S V_e K_g} \quad (2)$$

Correlated time histories of the increment in normal acceleration, the aircraft weight, and the aircraft equivalent airspeed were determined from the taped data; the gust factor was obtained from the plot of gust factor versus mass ratio in Reference 5. This particular factor is a variable and function of the mass ratio which, in turn, is equal to:

$$\mu_g = \frac{2W}{\frac{dC_L}{d\alpha} \rho c_g S} \quad (3)$$

43. The values of the derived gust velocity, which were determined for all of the penetrations, show that the greatest positive and negative values of this transfer function to be 45 and 54 feet per second, respectively, for the storms penetrated.

44. Bernoulli's equation for adiabatic flow of a perfect gas was used to calculate the ambient temperature. The temperature probe recovery factor was incorporated into the equation to account for the error involved in detecting the true temperature rise due to the dynamic heating. This recovery factor for the particular model probe used is better than 0.90. The subject equation was utilized in the following form:

$$T_{ic} = T_{ATM} + \frac{KM^2}{5} T_{ATM}$$

45. Calculation of the values of the vertical component of gust velocity, derived gust velocity, and ambient temperature was accomplished through the University of Dayton Research Institute (UDRI). This data, and the other taped data, were presented on computer printouts by UDRI. The printouts and all magnetic tapes containing the raw data for Phase I, 1966 and 1967, are available through the National Severe Storms Laboratory, Norman, Oklahoma.

EROSION DATA

46. The qualitative data from the erosion study consists of comparative information on the ability of various erosion-resistant materials to withstand the erosion found in the thunderstorm structure. This information, which is presented in the form of a chronological discussion, including photographs of any significant breakdown of any sample during the Phase I activities, can be found in Reference 6 for 1966 and Reference 7 for 1967, and, therefore, will not be elaborated upon in this report. However, the quantitative information, which was obtained during the 1967 Phase I flight series, is presented in the following paragraphs.

47. A quantitative measure of the erosion conditions penetrated was obtained by exposing a 1-inch-square area of Teflon to the environment (Figure 5) and calculating the weight loss per unit time of exposure. This resultant data is presented in Figure 20.

48. The calculated erosion rate data indicates that the degree of erosion was most severe during the first flight of 25 April and the flight of 18 May relative to the erosion rates attained during the other data flights. Comparison of this data with the data in the report on the visible deterioration of the erosion-resistant shoes shows that the greatest amount of deterioration to the shoes did not occur during the subject 25 April and 18 May flights but during the flight of 30 April when hail approximating a 0.5-inch diameter was encountered. The erosion rate calculated for this flight was negligible. This apparent discrepancy can be explained by the fact that the hail impact cut and tore the shoes rather than wore them down but had little adverse effect on the Teflon sample.

49. The magnitudes of the resultant erosion rate data were found to be relatively insignificant for a majority of the flights. In addition, some of the rate values are within a nebulous region which is due to the error in weight measurement of the Teflon samples. Future utilization of this method of measuring thunderstorm erosion conditions should be accomplished with a material which does not have the degree of tenacity of the Teflon yet would not break down into relatively large segments as does cork material.

RADIOSONDE EVALUATION

50. Initial radiosonde releases were achieved from the F-100F aircraft (Figure 1) while the aircraft was in VFR conditions over the Fort Sill restricted area in Southern Oklahoma, to preclude the hazard involved if the sonde would free-fall due to a malfunctioning parachute system. Although radiosonde release were planned while the aircraft was over or within a thunderstorm, these plans were never achieved because of unsuitable conditions over the test area.

51. The results of this evaluation have shown that release of radiosondes from high speed aircraft can be properly accomplished. The sonde can be tracked by radar to provide data on wind speed and direction while ground stations monitor the telemetered ambient pressures and temperatures. However, based on aircraft penetration experience, it is recommended that the parachute canopy should be strong enough to withstand hail and ice crystal encounter and the overall functional reliability of the parachute system should be quite high or releases should not be attempted over other than restricted areas.

HYGROMETER EVALUATION

52. The hygrometer system as installed for this program was designed to provide a measure of the quantity of solid and liquid water in an atmosphere saturated with water vapor. However, below certain pressure altitudes, this particular installation can monitor the dew-point temperature of an atmosphere containing water only in the vapor state. The sampling of an atmosphere unsaturated with respect to water vapor, yet containing a quantity of liquid and/or solid water, would result in dew-point temperatures greater than the atmospheric dew point because of the unknown quantity of liquid and/or solid water vaporized by the compressor and mixed with the atmospheric gas sample.

53. The following equation was used to determine the quantity of liquid and/or solid water in a saturated atmosphere. The pressures are in units of pounds per square inch, absolute, and the temperature is in degrees Rankine. The constant H is the result of grouping various other constants and conversion factors in order that the output values of w will be in grams per cubic meter

$$\frac{(H = 2.69 \times 10^4 \text{ grams in}^2 \text{ R}^\circ)}{\text{lb m}^3} \quad (4)$$

$$w = P_{wSAM} H \frac{(P_{ATM} - 1)}{P_{GL} T_{ATM} T_{GL}} \text{ grams/m}^3$$

Equation 4 was derived through use of the perfect gas laws in the following manner:

$$P_w V_w = m_w R_w T_w; \quad P_a V_a = m_a R_a T_a$$

$$r = \frac{m_w}{m_a} \text{ (definition of mixing ratio)}$$

$$T_a = T_w; \quad V_a = V_w; \quad R_a = 53.35 \text{ ft lb f / lb m R}^\circ; \quad R_w = 85.78 \text{ ft lb f / lb m R}^\circ$$

$$r = \frac{0.622 P_w}{P_a}$$

54. The quantity of water for a unit volume of air is equal to the product of the mixing ratio and the density of the dry air. In mathematical form,

$$w = r \rho_a = \frac{0.622 P_w P_a}{P_a R_a T_a} = \frac{2.69 \times 10^4 P_w}{T_a} \quad (5)$$

In the meteorological range of pressure and temperature the assumption that the saturation vapor pressure of pure water is equal to the saturation vapor pressure for moist air incorporates an error in pressure of 0.5% or less. Therefore, the vapor pressure can be assumed to be a temperature-dependent function only. The absolute atmospheric humidity in the cloud according to Equation 5 would be:

$$w_{ATM} = \frac{H}{T_{ATM}} P_{wATM} \quad (6)$$

Since it is assumed that the air space enveloped by the cloud is saturated with water vapor, P_{wATM} can be found in Reference 8 as a function of T_{ATM} .

This temperature is, in turn, sensed by a total temperature probe. The vapor concentration in the gas sample line would be:

$$w_{\text{SAM}} = \frac{H}{T_{\text{GL}}} P_{w\text{SAM}} \quad (7)$$

55. The source of the gas-line temperature was an iron constantan element mounted in the gas line (Figure 16). The hygrometer provided the dew-point temperature for the sample. This temperature and the hygrometric tables provide the partial pressure of the water vapor. The resultant gas sample vapor concentration found is then transferred to atmospheric conditions by the following relationship:

$$\frac{P_{\text{GL}} V_{\text{GL}}}{P_{\text{ATM}} V_{\text{ATM}}} = \frac{R T_{\text{GL}}}{R T_{\text{ATM}}}$$

$$V_{\text{ATM}} = \frac{(P_{\text{GL}} T_{\text{ATM}})}{P_{\text{ATM}} T_{\text{GL}}} V_{\text{GL}} \quad (8)$$

$$\text{Therefore, } w'_{\text{ATM}} = \frac{(P_{\text{ATM}} T_{\text{GL}})}{P_{\text{GL}} T_{\text{ATM}}} w_{\text{SAM}}$$

The quantity of liquid and/or solid water encountered would then be equal to $(w'_{\text{ATM}} - w_{\text{ATM}})$ grams of water per cubic meter of dry air which is Equation 4.

56. Obtaining the dew-point temperature for an atmosphere whose water is all in the vapor state involves a slight deviation from the analysis of the saturated atmosphere. In this case, w'_{ATM} will equal the absolute atmospheric humidity as given by Equation 6. Therefore, inserting the value of w_{ATM} as given by Equation 6 and the value of w_{SAM} as given by Equation 7 into Equation 8 yields the following relationship:

$$\frac{H}{T_{\text{ATM}}} P_{w\text{ATM}} = \frac{P_{\text{ATM}} T_{\text{GL}}}{P_{\text{GL}} T_{\text{ATM}}} \frac{(H P_{w\text{SAM}})}{T_{\text{GL}}} \quad (9)$$

$$P_{w\text{ATM}} = \frac{P_{\text{ATM}} P_{w\text{SAM}}}{P_{\text{GL}}}$$

The value of dew-point temperatures corresponding to $P_{W_{ATM}}$ is then found in the hygrometric tables.

57. The hygrometer system was available for use during flights 17 through 22, inclusively, of Phase I, 1967. Values of dew point were obtained from the start of the climb to the start of the first penetration utilizing Equation 8. This data is presented in Figure 21 for three of the six flights involved. These flights were chosen for presentation because they each occurred during the time the reference radiosonde data was taken. The difference between the radiosonde data and the hygrometer data is discussed in the following paragraphs.

58. The maximum temperature depression attainable for the thermoelectric cooler of the sensor is a linear function of the ambient temperature of the environment containing the sensor (Reference 9). The installation of the sensor is such that the temperature of the sample is an indication of the ambient temperature of the atmosphere containing the sensor. Based on this fact, the approximate design limit of the system is shown in Figure 21 by the shaded areas. This shows the dew-point temperature of the atmosphere was below the design capability of the system from a pressure altitude of 14,000 feet up to the penetration altitude, which was 20,000 feet for these flights. The difference shown in dew point for altitudes below 14,000 feet is believed to be the result of failing to obtain a truly representative sample through the flush-mounted bleed port. This is attributed to the high rate of gas flow at this point in the engine. Apparently the utilization of the static pressure differential between this point in the engine and the atmosphere will not ensure procuring a suitable sample.

59. The fluctuations and peaking of dew-point temperature expected due to the liquid and/or solid water encountered during the penetration of the storm clouds were not observed in the data recorded on the magnetic tape. It is a fact that quantities of liquid and/or solid water were present in the cells in various places in the clouds. Since an indication of these quantities was not recorded, it is speculated at this time that this was due to the nonrepresentative sample obtained.

60. Insufficient quantitative information was obtained with which to determine whether or not such a method of obtaining time histories of the quantities of solid and/or liquid water in the thunderstorm is feasible. However, the author believes further study of the method is merited. However, the two most significant changes required in the system before future study should be considered are: (1) to expose the hot side of the thermoelectric cooler to a colder atmosphere, thereby increasing the radiative and convective dissipation of the heat; and (2) to insert a total pressure probe into the bleed-off port to obtain a representative sample of the gas.

SECTION V

DISCUSSION (PHASE II)

61. Data recorded on magnetic tape for the AFCRL during Phase II is shown in Table IV. Supplemental data recorded by means other than tape provided insight to the electrical activity to which an aircraft is exposed while within or near a thunderstorm environment. This additional quantitative and qualitative data includes a measure of the peak currents, time duration to half value and overpressure associated with a lightning strike to the aircraft, in addition to color film of the electrical activity on the aircraft extremities.

62. The peak currents, time duration to half value, and overpressure were obtained by film coverage of the oscilloscope presentations in the wing tank. A part of the resultant data is presented in Table IV through the courtesy of the Sandia Corporation. A detailed analysis of the thunderstorm lightning film was accomplished by the Sandia Corporation and the findings are presented in Reference 10.

63. The study of 1300 feet of 16mm color film exposed to document electrical activity occurring on the aircraft, which resulted in finding 33 frames showing such activity, was accomplished by the Adverse Weather Section, Flight Test Engineering Division, ASD. The results of this study are presented in this report along with enlarged prints of 12 frames of special interest. All frames are not presented because: (1) similarity exists between some of the strikes; (2) the quality of some of the frames was poor; or (3) clarity and distinction were reduced to an unacceptable level when such frames were enlarged to the figure size desired for this report.

64. Reference should be made to Figures 22 and 23 and the associated legend to properly interpret Figures 25 through 34. Those figures with the same series number in their title pertain to the same strike-discharge.

65. It was determined that the test F-100F aircraft has eight areas on which all strikes and discharges occurred. These areas are the noseboom, wingtips, the horizontal stabilizer tips, vertical stabilizer trailing edge, the

eyelids of the afterburner section, and the tail of the left-wing tank. There is no discernible relationship between the strike and discharge points based on an examination of the photographs. However, such an examination coupled with knowledge of the associated electric fields may produce such a relationship.

66. The majority of the strikes were to the noseboom; the vertical stabilizer appeared to be the second most vulnerable component. The wingtips and the horizontal stabilizers were the points of discharge. Electric activity was noted on the afterburner twice and once on the tail of the wing tank. No such activity was observed on other areas of the aircraft.

67. The most spectacular example of the lightning activity recorded is presented in Figures 25 through 29. The noseboom and the vertical stabilizer received the strikes and the right wing probe served as the discharge point. The activity on the boom (Figure 25) occurred when the film was moving in the camera and, had not the shutter been removed, the initial strike and restrikes to the noseboom would not have been filmed. Figure 24 provides a history of this occurrence in a time lapse sequence. In Sequence A of Figure 24, the aircraft and film frame are motionless with respect to the aircraft frame of reference (xyz coordinate system) but moving with a velocity dY/dt relative to an earth frame of reference (XYZ coordinate system.) During the 1-second interval (Reference paragraph 25), the radiation passing through the neutral density filter and lens to the film produces an image of the noseboom on the exposed frame. After the 1-second exposure, the next film frame begins to move in front of the lens at a rate dx/dt relative to the aircraft and the xyz coordinate system as shown in Sequence B. It was during this instant that the initial lightning stroke came in contact with the noseboom and the image of the channel was documented on the film frame. The next current surge occurred after a time interval dt when the aircraft had moved a distance dY (Sequence C). The path of this second current surge closely approximated the path of the prior surge; however, the influx of light from this stroke channel was focused on a different section of the frame because of aircraft movement which resulted in a parallel image of the lightning on the frame. If this procedure were repeated a number of times, the result would be a series of roughly parallel strikes to the noseboom (Figure 25).

68. Figure 25 would have resembled Sequence C with two parallel images of the noseboom on the same frame had there been enough light to affect the film and produce the second noseboom image. Since there was not sufficient light, Figure 25 resembles sequence D in which the true position of the noseboom is not shown with respect to the lightning strikes and therefore the strikes appear to be terminating in mid air. This occurrence emphasizes the fact that the drop off in light intensity in a radial direction from the centerline of the ionization path is quite rapid.

69. The extreme brightness of the horizontal discharge channel from the wingtip (Figures 26 and 27) is the result of superpositioning about five restrikes on the same section of the film frame because of no relative movement between these restrikes and the frame. The discharges from the wingtip shown in this series and the other series, show that the discharge follows the same path from the wingtip which suggests something must always be present during the flight which dictates channel propagation. It is hypothesized that the channel follows the center of the vortices because this is a low pressure regime and the potential difference required to produce a spark is directly proportional to the atmospheric pressure.

70. Figure 27 presents another interesting phenomenon regarding the parallel, vertical channels at their junction with the horizontal wingtip discharge. At least four of the restrikes follow a spiral path into the wingtip discharge. Apparently the paths conform to the motion of the wingtip vortex since this would be the path of decreasing pressure and therefore least resistance. This occurrence was noted only during this one instance.

71. Considering the fact that the light intensity is directly proportional to the current implies that the fifth restrike in Figures 26 and 27 to be of the highest current with a progressive decrease in current flow in the restrikes before and after the fifth one.

72. Examination of the various series shows that in a majority of the cases the noseboom was one of, or the only strike point. This suggests either or both of the following possibilities. First, that the aircraft triggers the discharge

as it approaches the fields nearby, or, if the discharge has already been triggered, that the aircraft alters the path of the ionization channel by providing a path of lesser resistance than the atmosphere for the current flow. Insufficient information is presently available with which to determine whether either of these possibilities is fact.

73. Table IV shows one discharge to have been recorded through the left wing tip (this particular discharge was not found on the film), and offers ground for speculation that the 450-gallon instrumented tank under the left wing has an effect on the current path. This can only become a speculation since there were no recording instruments to detect the path of the current through the aircraft.

74. The Sandia Corporation camera installation focused on the underside of the fuselage did not record any movement of restrike or discharge channels along the underside of the fuselage nor was any such activity observed along the back of the aircraft fuselage. The author feels that, based on this experience plus the fact that this aircraft was committed to penetrating storms to encounter lightning, the opportunity to observe this type of channel movement with this aircraft would be rare.

75. Reference 11 mentions streamers being emitted from various points of the aircraft as the strike approaches the aircraft. These streamers were not visible in any of the film although it is possible they could have existed but were not of sufficient light intensity to affect the film.

76. The most interesting fact about the series 2 through 4 is that the point of discharge from the aircraft was within approximately 12 inches of the main fuel vent outlet (Figure 22) while the aircraft was in the temperature altitude regime in which JP-4 fuel is explosive (Reference 13). These strike occurrences indicate that a vent located near an aircraft's extremity is quite vulnerable to a direct strike discharge.

SECTION VI

AIRCRAFT DAMAGE

77. This test F-100F aircraft probably sustained more lightning strikes than any aircraft of its type during a normal aircraft life span, yet the most severe damage ever received as a result of a lightning strike consisted of concentrated points at which the aircraft metal was melted by a strike or discharge (Figures 25 and 36). The fact that the aircraft received relatively little damage is attributed to the protective devices installed. These devices consisted of a nitrogen purge system, various probes on the aircraft extremities, and a metal strip over the top of the canopy.

78. The nitrogen purge system was designed to keep an efflux of fuel-nitrogen vapor through the main fuel vent outlet in the vertical stabilizer. It was installed because LTRI laboratory tests (Reference 12) indicated flame propagation into this vent system was a definite possibility.

79. The wing tips and the vertical stabilizers were protected by the aluminum probes mounted at these points. The probes received the burns instead of the wingtips or the stabilizer. A different type of probe, classed as diverter-discharges, protected the horizontal stabilizers. These diverter-discharger probes served as static dischargers as well as burn points for the lightning discharges.

80. The third type of protective device used on the aircraft was a metal strip installed along the length of the canopy (Figure 11). It was installed because the LTRI simulated natural lightning tests on a salvaged F-100F canopy (Reference 12) indicated it is feasible that a strike approaching the canopy area could cause streamers to form at various locations within the cockpit and that the strike channel could make contact with one of these streamers by piercing the canopy if there were not a more suitable point of contact such as the metal strip.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

81. In conclusion it can be stated that the data obtained as a result of this program presents an approach towards the achievement of complete and thorough understanding of the complexities of severe storms as well as the identification and production of accurate and reliable models of thunderstorms. However, it is obvious that there is still a great quantity of data needed to explain in more precise detail the mechanism of the thunderstorm and its associated electrical phenomena. Aircraft such as the test aircraft, in this report will likely continue to be involved in similar programs in the future, so that the following recommendations should be considered for that aircraft as well as for other all-weather types of aircraft:

a. Such aircraft should be subjected to simulated natural lightning strikes before flights are made into or about thunderstorms to determine the effect of strikes on the aircraft.

b. A proven flame arrestor should be installed in the fuel vent systems of all-weather aircraft if the particular vent position is considered vulnerable.

c. Diverter-dischargers should be installed on the extremities of all-weather aircraft.

d. The nitrogen purge system, the diverter-dischargers, and the metal strip over the canopy should be reinstalled should the F-100 aircraft be used in future thunderstorm studies.

82. The conclusions reached regarding the data-gathering procedures are:

a. Radiosonde release into particular cells of a thunderstorm system is a feasible method of obtaining data from storm systems too severe to penetrate with an aircraft.

b. The dew-point analysis of engine hot bleed air for water content and for relating this data to atmospheric conditions should be studied further to determine whether this is a valid method of obtaining data on liquid and/or solid water content inside and around the perimeter of thunderstorm systems.

c. The exposure of material to the erosion environment penetrated by an aircraft is a feasible method of obtaining quantitative information on the relative degree of erosion encountered.

d. The probe-camera-oscilloscope combination is a reliable and satisfactory method of obtaining data on lightning strikes to and discharges from an aircraft.

e. Successful utilization can be made of rockets trailing wires to increase the probability of aircraft contact with a cloud-to-ground lightning strike.

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TABLE I
PROJECT AIRCRAFT AND FLIGHT ACTIVITIES

<u>AIRCRAFT</u>	<u>PURPOSE</u>		
F-100F	Penetrate Storms Dropsonde Releases Lightning Study		
T-33	Chase		
	PHASE I		PHASE II
	1966	1967	1966
Days spent at test site	50	43	31
Days during which storms were available	15	20	14
Data flights at test site	18	23	14
Number of thunderstorm penetrations	76	163	105
Minutes of data collected (approx.)	264	440	600
Number of recorded lightning strikes (approx.)	---	---	16
Induced cloud-to-ground lightning strikes	---	---	0

TABLE II
THUNDERSTORM DATA ACCUMULATED DURING PHASE I

PARAMETER	1966		1967	
	*Indicates data that were not satisfactory			
1. True Vertical Gust Velocity				
2. Effective Gust Velocity				
3. Normal Acceleration				
4. Altitude				
5. Airspeed				
6. Differential Altitude				
7. Ambient Temperature				
8. Infrared Temperature				
9. Control Positions				
10. Aircraft Magnetic Heading				
11. TACAN Bearing/Range				
12. Aircraft Fuel Remaining				
13. Ice Formation Conditions				
14. Erosion Intensity				
15. Cloud Formation Film				
	28 April		19 April	
	10 May		20 April	
	11 May		21 April	
	20 May, Flt 1		25 April, Flt 1	
	20 May, Flt 2		25 April, Flt 2	
	23 May, Flt 1		29 April	
	23 May, Flt 2		30 April	
	30 May		5 May, Flt 1	
	3 June		5 May, Flt 2	
	5 June		13 May	
	7 June		18 May	
	8 June		19 May	
	15 June		20 May, Flt 1	
			20 May, Flt 2	
			27 May, Flt 1	
			27 May, Flt 2	
			28 May, Flt 1	
			28 May, Flt 2	
			30 May, Flt 1	
			30 May, Flt 2	

TABLE III
THUNDERSTORM DATA ACCUMULATED DURING PHASE II

PARAMETER	AUGUST 1966												
	4	5	8	9	10	12	15	16	19	22	23	24	26
1. True Vertical Gust Velocity													
2. Normal Acceleration													
3. Altitude													
4. Airspeed													
5. Differential Altitude					*								
6. Ambient Temperature													
7. Infrared Temperature											*		
8. Control Positions													
9. Aircraft Magnetic Heading													
10. TACAN Bearing/Range													
11. Aircraft Fuel Remaining													
12. Ice Formation Conditions													
13. Cloud Formation Film													
14. UHF ARN-6 Receiver Noise	*	*	*										
15. Electric Field			*										

TABLE IV
1964 LIGHTNING CURRENT DATA

PHOTO NUMBER										1. ROSEBOM										2. RIGHT WING				3. VERTICAL STAB.				4. LEFT WING	
DATE AUG. 1964	LOCAL TIME	SARADIA TEST ZNR--	PASS	ALT KFT	TANK CAMERAS		A/C CAMERAS		FRAME	PEAK AMPS	RISE A/S	DECAY A/S	FRAME	PEAK AMPS	RISE A/S	DECAY A/S	FRAME	PEAK AMPS	RISE A/S	DECAY A/S	FRAME	PEAK AMPS							
					Man in P.L.	3mm 30" LENS	HOSE BOOM	COCKPIT AFT WIDE ANGLE																					
4	Not determined	91	4	28		Risk Installed	1	2																					
10	Not determined	101	4	26		51		4																					
17	14:25:20	102	3	26		47		5	+1200				9609	-1455	330	100													
19	14:31:31	105	4	21	53 & 54	53 & 56	0	12 & 13	Camera Jammed				0430	-1455	330	100													
19	14:40:53	103	4	21	37 & 58	59	Out of Film	9124	+800	830	275		0455	+4000															
22	14:48:00	106	3	21 or 20	60		14	35					0554																
22	14:48:06	108	3	21 or 20	61		15	17	+2800	3000	420		0555	-2300	2100	700													
22	14:51:17	106	4	21 or 20	63 & 64		16	38 & 19	+2800	600	170		0558																
23	14:53:56	107	2	26			20	22					0677																
23	14:54:08	107	4	30	6.		21	23 & 36	+1300		100		0700	+260															
23	15:03:03	107	5	30	67		Out of Film	9380					0711	-720 +260															
23	15:07:04	107	4	31	68		Out of Film	9366					0719	-500															
23	15:12:22	107	4	31	69 & 70		Out of Film	9380					0721	+300															
24	14:54:35	108	3	23	71		24	26	+3000	850	80		0835	-3200	600	80													
24	14:56:14	108	4	24	73		25	27	+2000	270	150		0863																
24	15:08:08	108	8	24			Out of Film	9461					0892																
25	14:51:43	108	3	37			28	31					1053																
25	15:00:52	109	4	37			29	37					1063																
25	15:22:30	109	7	37			30	32	+2500		230		1079																
25	15:23:08	109	7	37	79		31	33					1080	-4000	170	20													
25	15:32:17	109	8	37			Out of Film	9747	+4600	800	440		1093																
25	15:32:24	109	8	37	87		Out of Film	9787					1098																

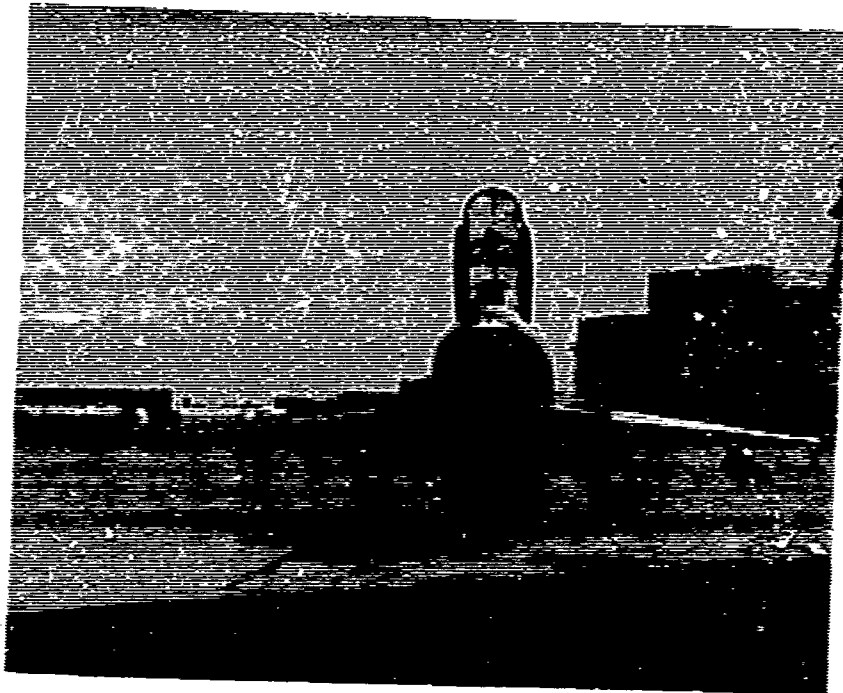


Figure 1. The F-100F Penetration Aircraft - Phase I. (A dropsonde is shown mounted under the left wing. The pylon under the right wing was installed to carry a second sonde.)

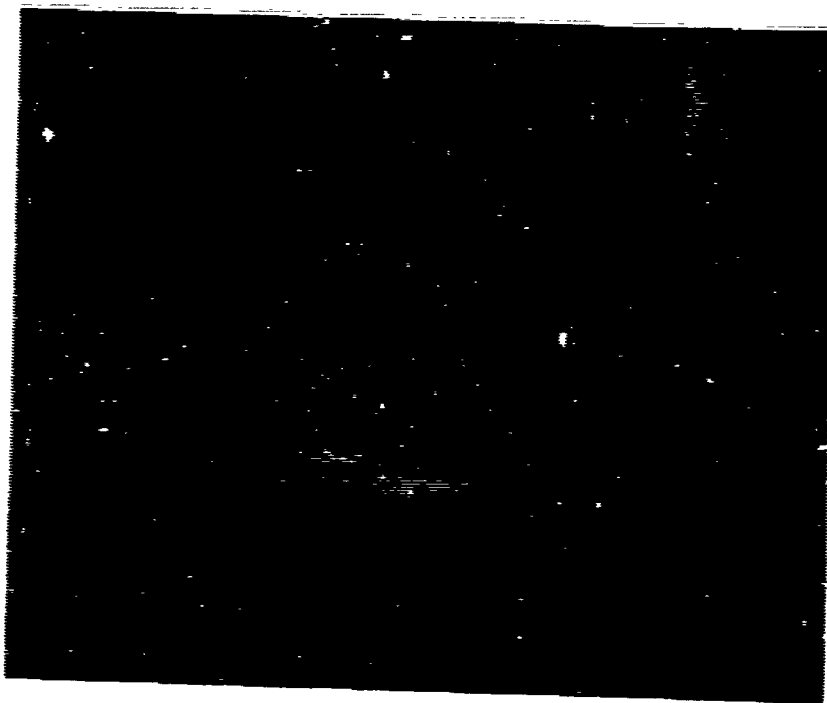


Figure 2. The F-100F Penetration Aircraft - Phase II.

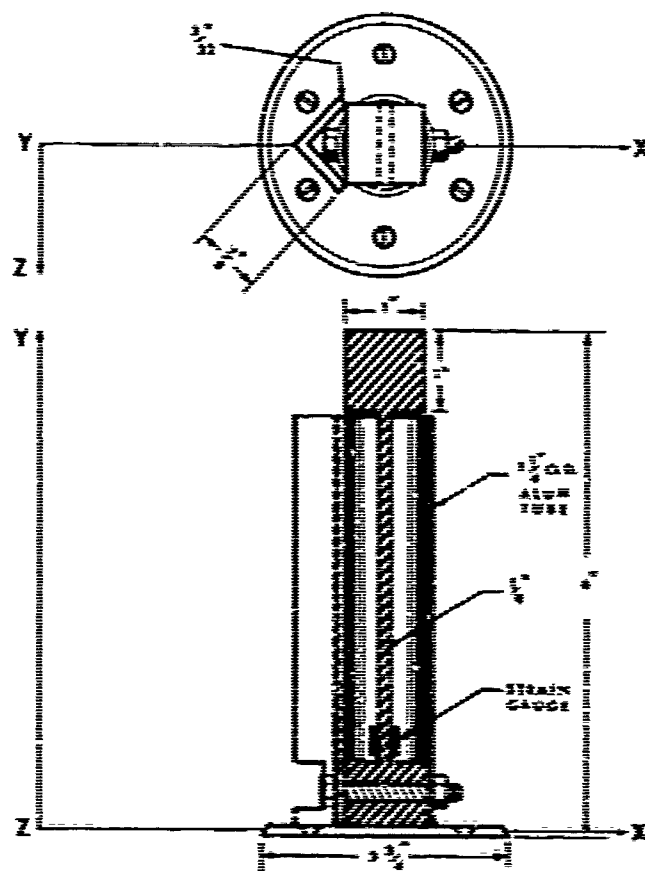


Figure 3. Side and Top View of a Nail Probe

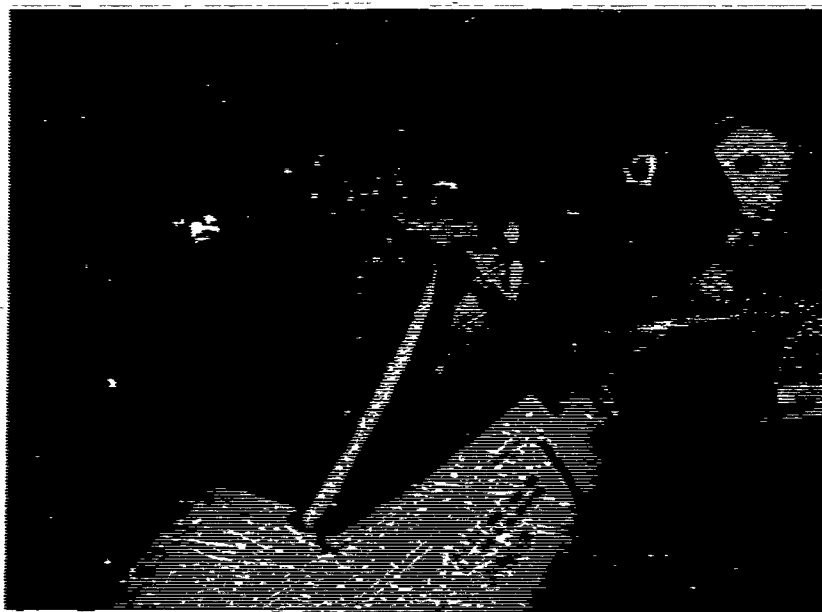


Figure 4. The 16mm Time-Lapse Camera and the Multichannel Analog Tape System in Their Respective Cockpits

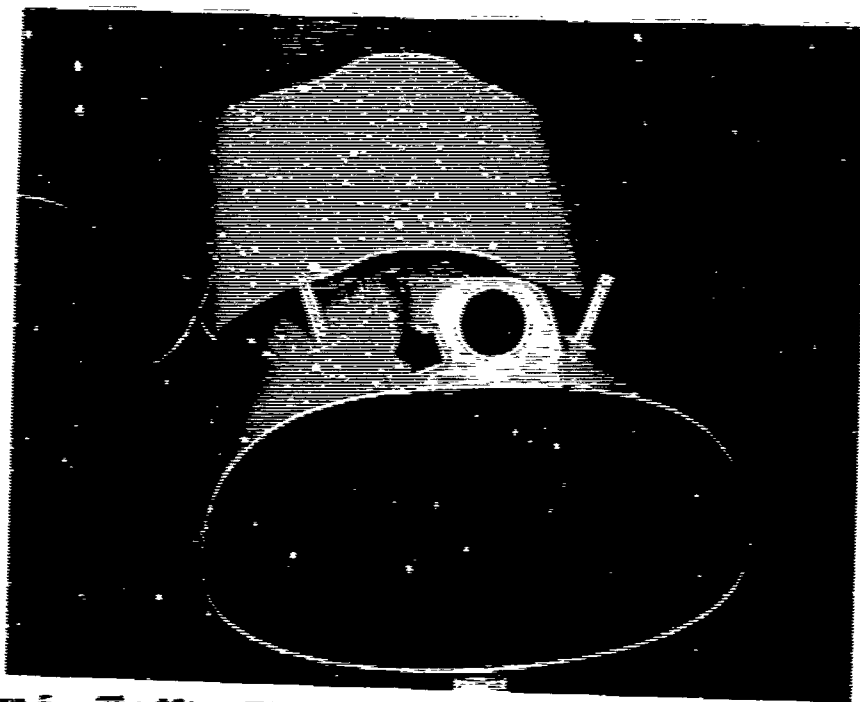


Figure 5. The 35mm Time-Lapse Nose Camera and the Teflon Erosion Sample Mount (Arrow points to erosion block.)

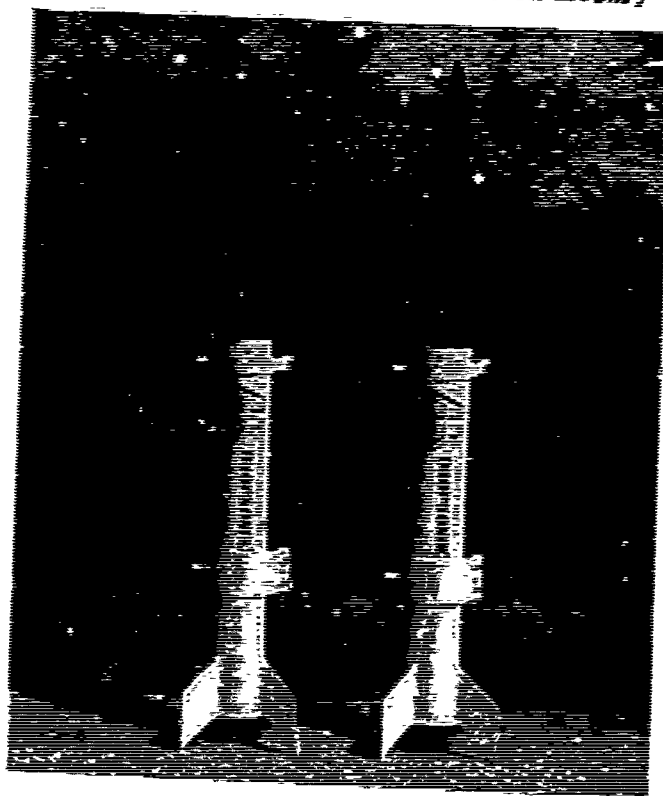


Figure 6. Two of the Dropsondes Released from the F-100F Aircraft

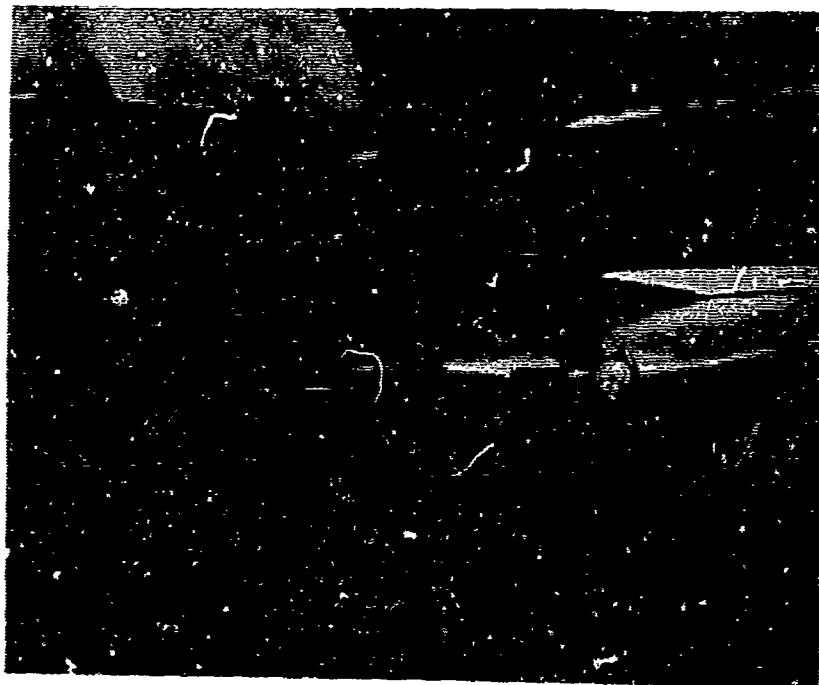


Figure 7. The Lightning Probe, Electric Field Mill, and Static Dischargers Mounted on the Aircraft Wingtip



Figure 8. The Lightning Probe and Main Fuel Vent Outlet in the Vertical Stabilizer

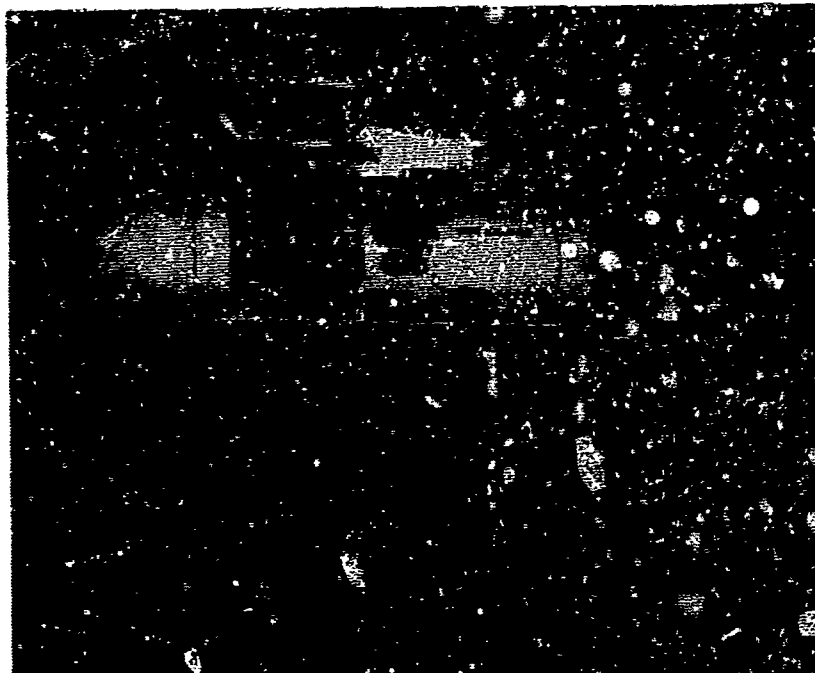


Figure 9. The 150-Gallon Instrumented Tank Under the Left Wing



Figure 10. The 16mm Nose Lightning Camera and the Noseboom Current Shunt Housing

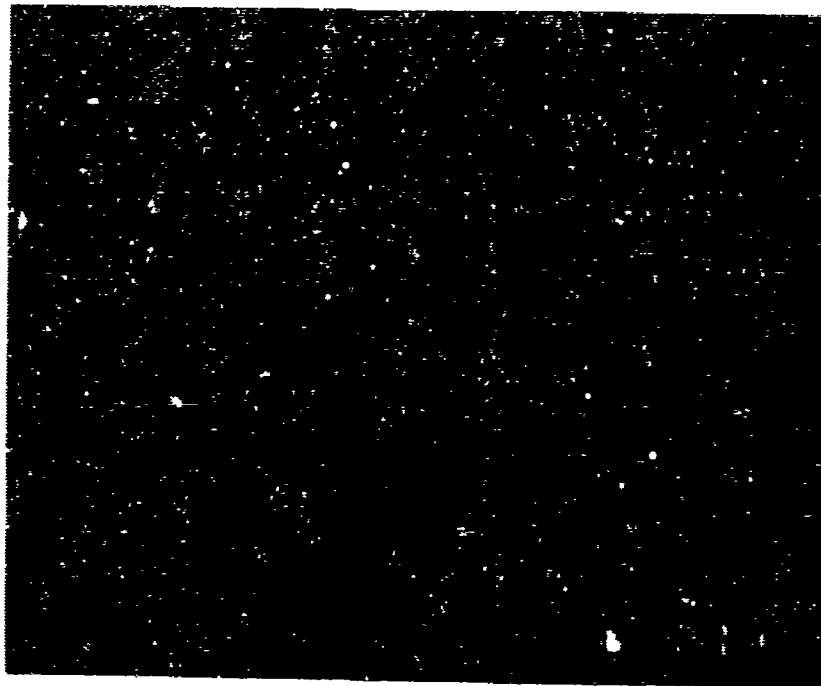


Figure 11. The 16mm Tail Lightning Camera and the Canopy Protector Strip



Figure 12. Cutout Section of the Wing Tank for the Tank Cameras



Figure 13. Instrumentation Controls in the Front Cockpit

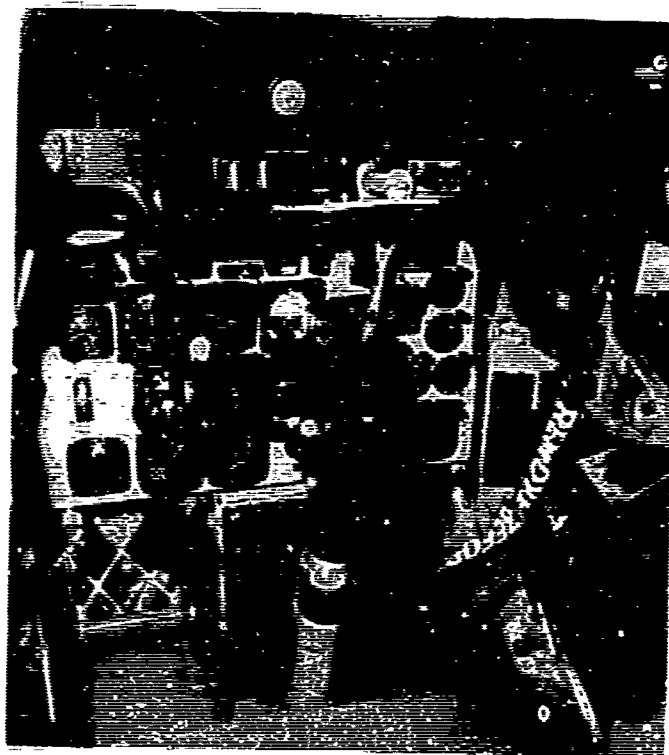


Figure 14. Instrumentation Controls in the Front Cockpit

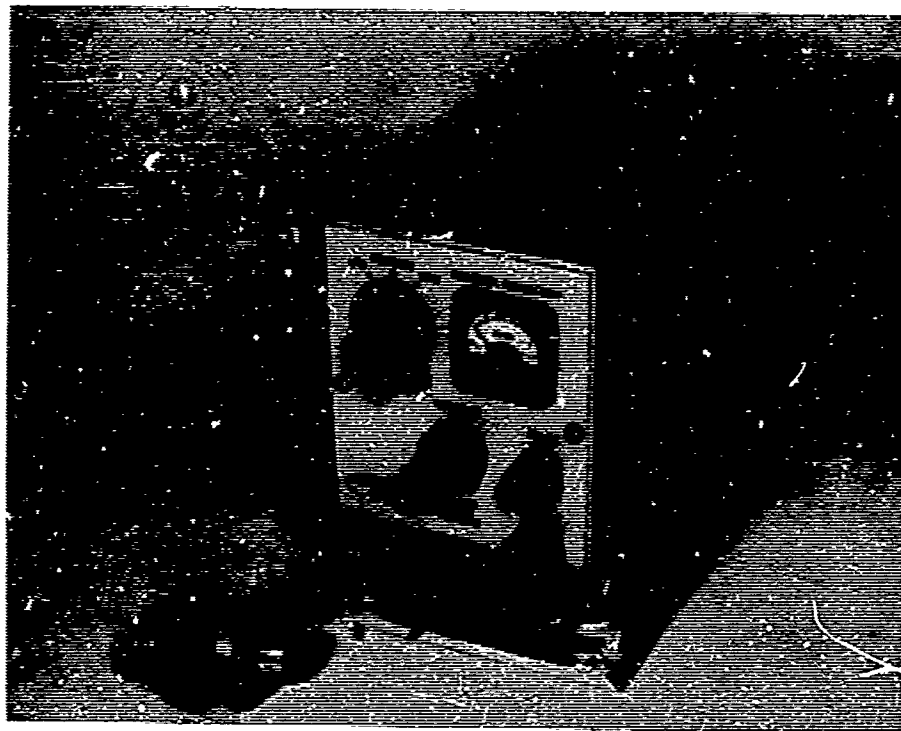


Figure 15. The Hygrometer Sensor and Control Unit

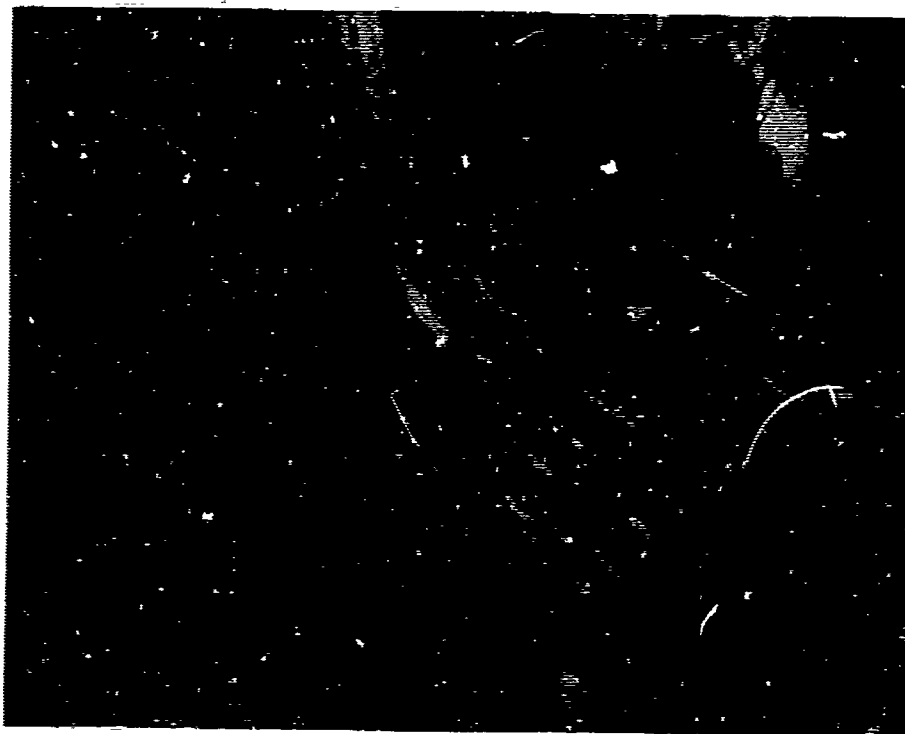


Figure 16. The Sensor Mounted in the Underside of the Aircraft Fuselage (The hygrometer sensor and mounting block (1), sample line static temperature sensor (2), and static pressure sensor (3), mounted on the underside of the F-100F fuselage in front of the tail hook yoke.)



Figure 17. The Gas Sample Tubing from the Engine to the Sensor
(The arrows indicate the flush-mounted bleed-off port behind the low pressure compressor and the start of the sample line vacuum insulated tubing.)

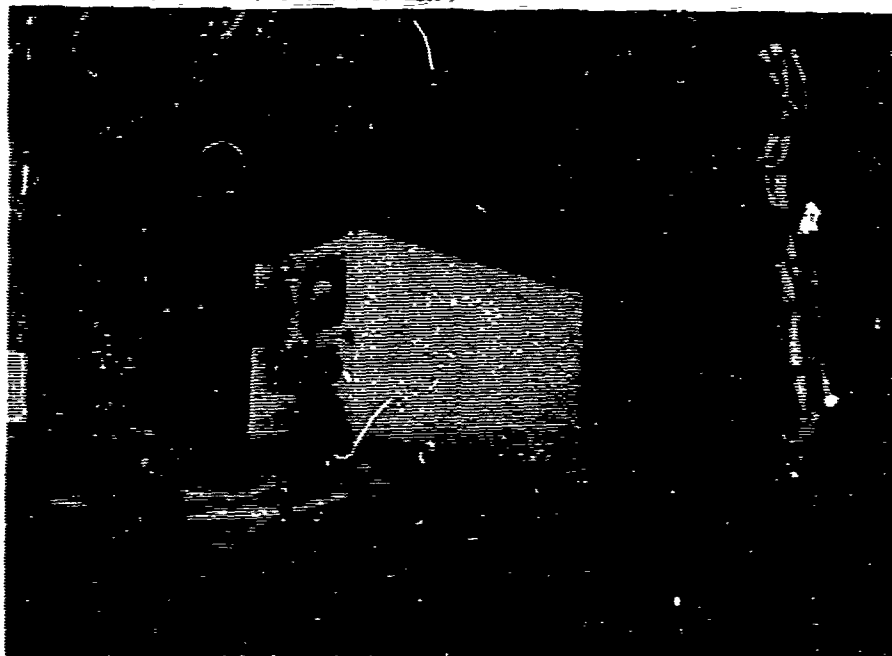


Figure 18. The Hygrometer Control and Calibration Units Mounted in the Left Gun Bay.



Figure 19. The Research Vessel "Thunderbolt"

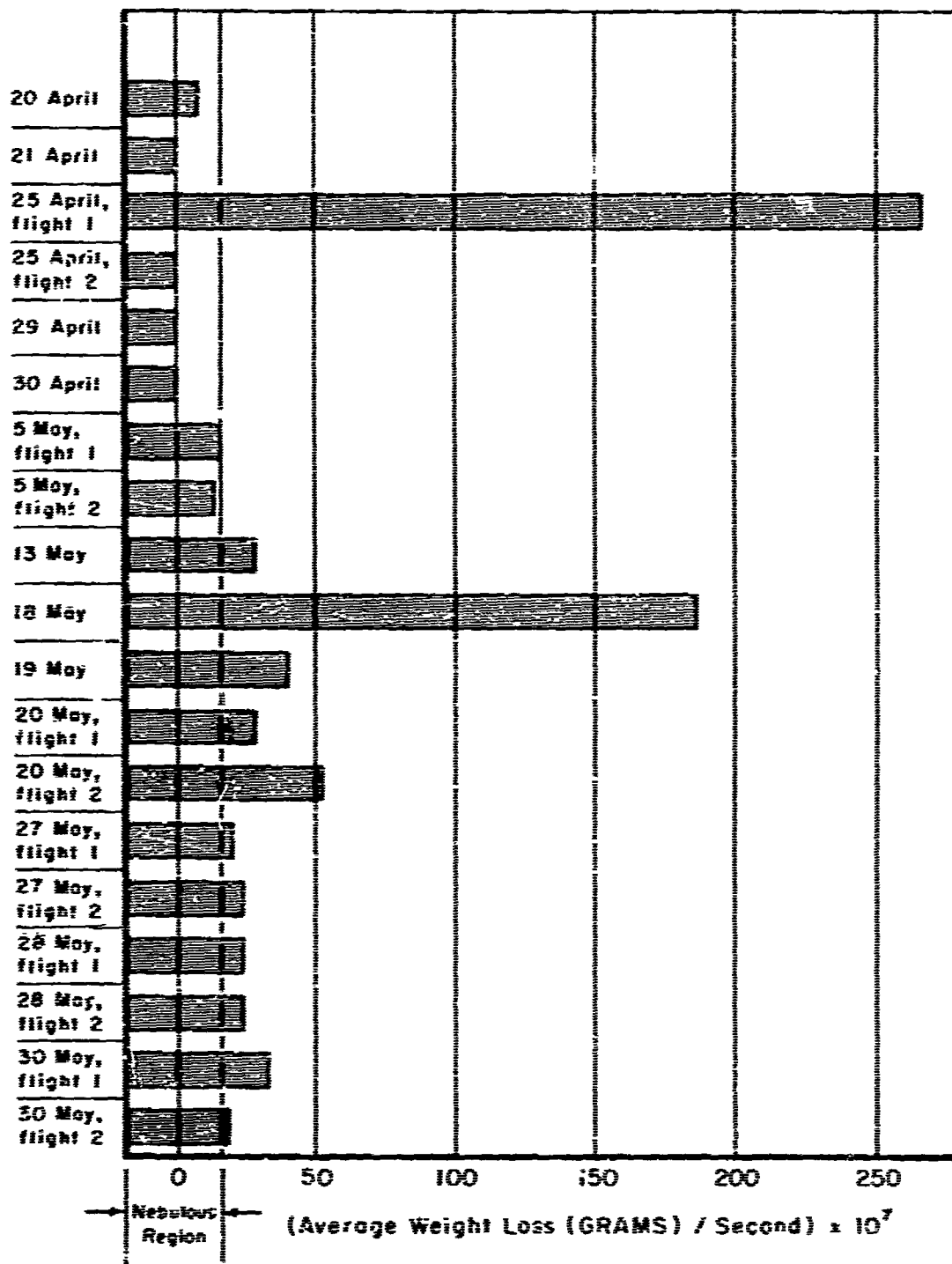


Figure 20. Teflon Erosion Rate Data Presentation

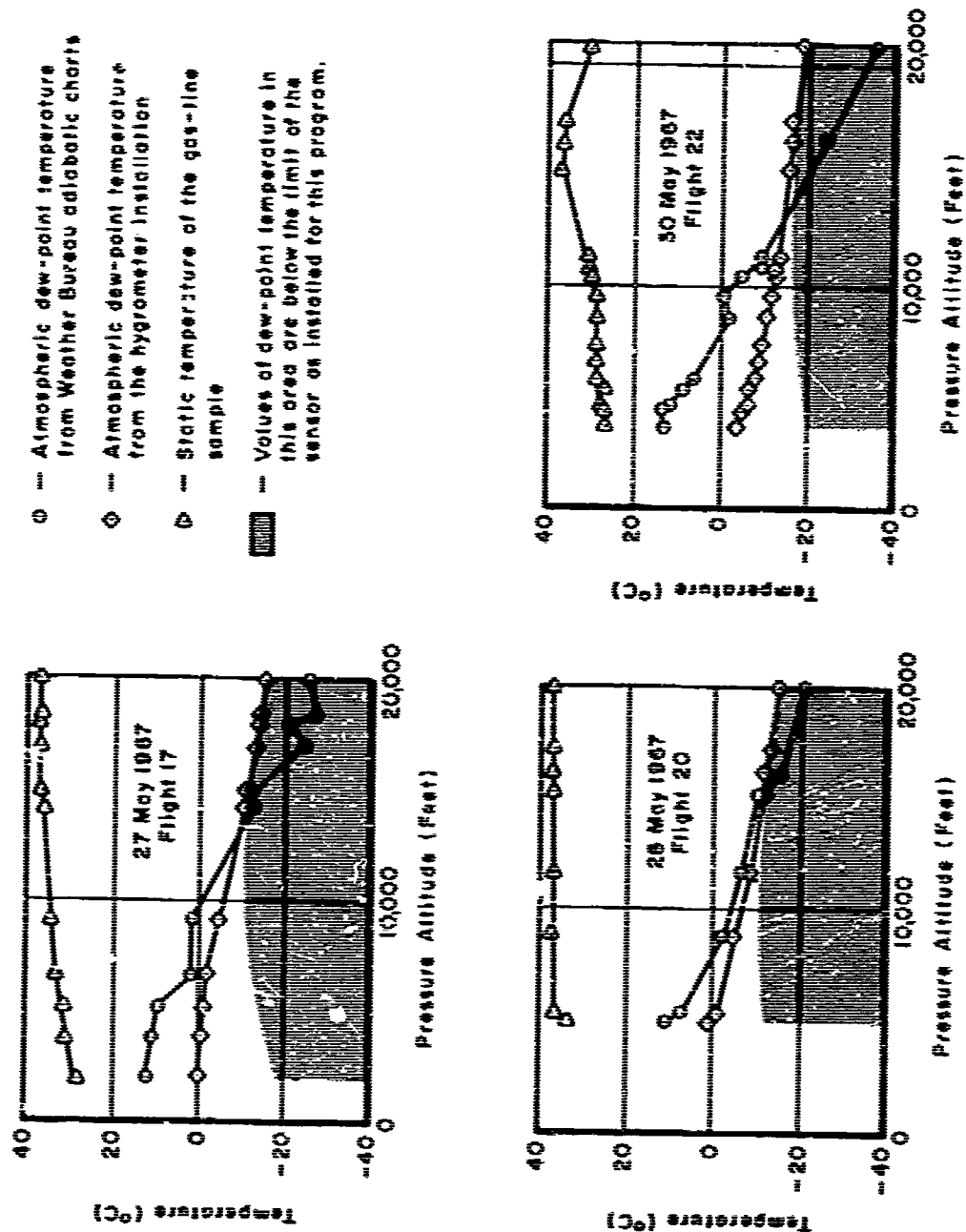


Figure 21. Hygrometer Installation Dew-Point and Radiosonde Dew-Point versus Pressure Altitude

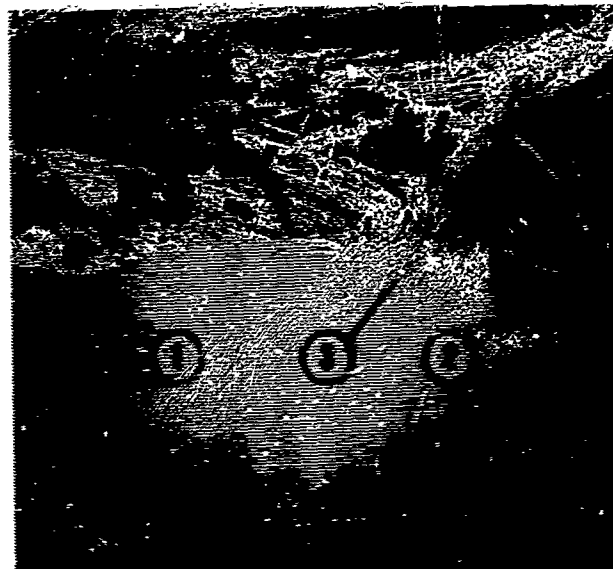


Figure 22. Series 2. Lightning Discharge from the Trailing Edge of the Vertical Stabilizer. (Figure shows: (1) Aircraft noseboom; (2) Left horizontal stabilizer; (3) Main Fuel Vent Outlet.)



Figure 23. Series 2. Lightning Discharge from the Left Stabilizer Diverter-Discharger and the Vertical Stabilizer Trailing Edge.

Legend:

- | | |
|------------------------------------|--|
| (1) Right wing aerodynamic fence; | (5) Vertical stabilizer lightning probe; |
| (2) Right wingtip lightning probe; | (6) Left horizontal stabilizer; |
| (3) Right horizontal stabilizer; | (7) Left wingtip lightning probe; |
| (4) Canopy protector strip; | (8) Left wing aerodynamic fence. |

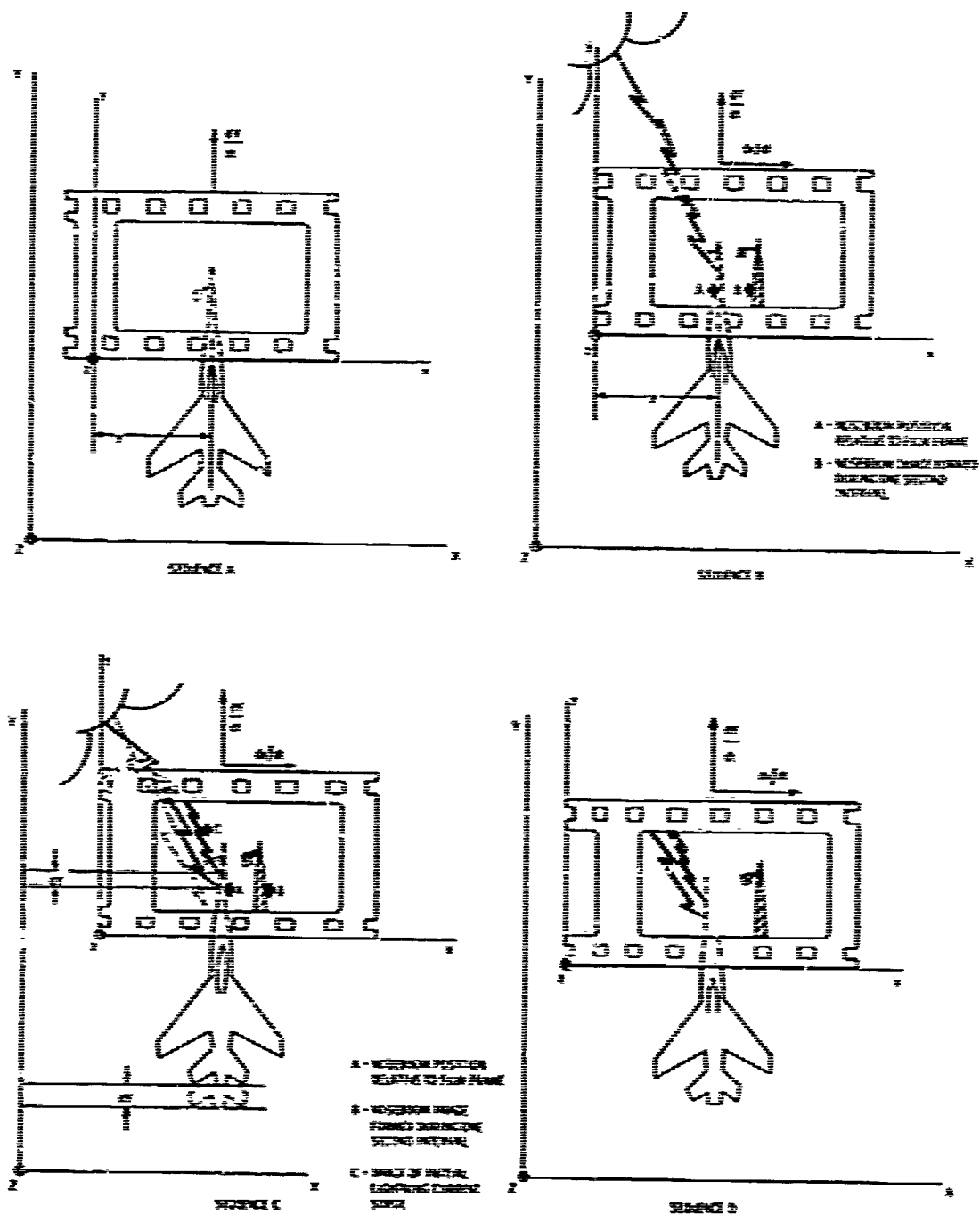


Figure 24. Time Sequence Explaining the Parallel Imagery on Some of the Lightning Frames



Figure 25. Series 1. Lightning Strike to the Aircraft Noseboom

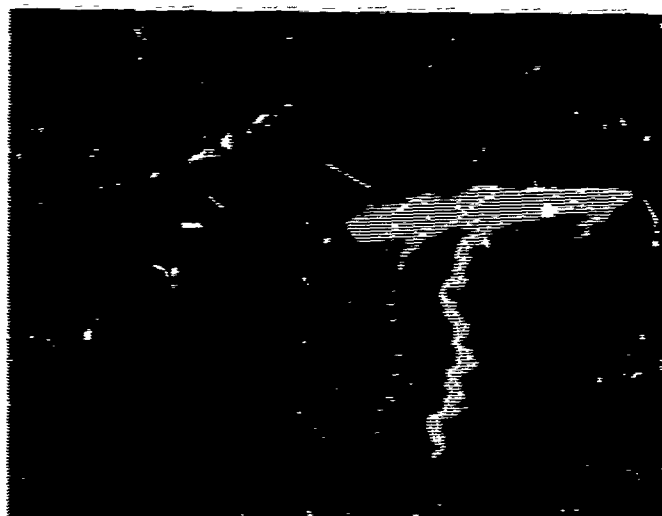


Figure 26. Series 1. Lightning Discharge from the Right Wingtip Probe

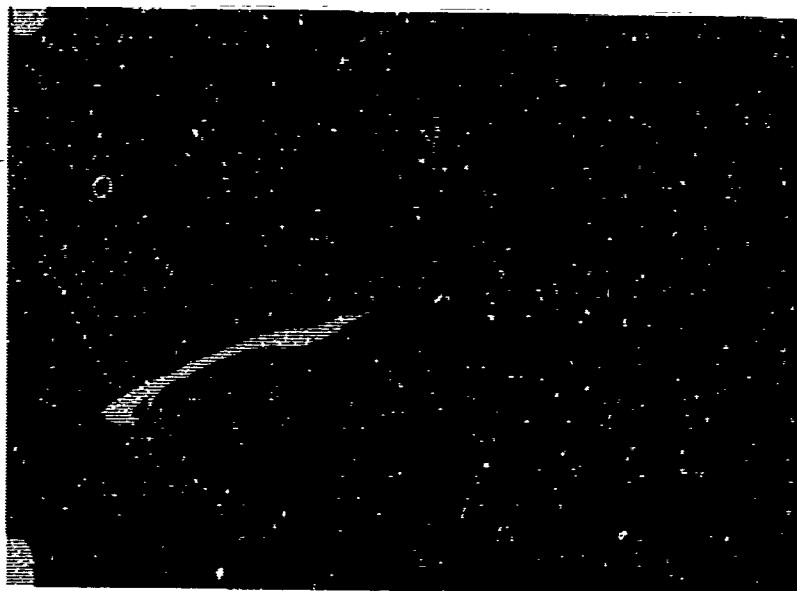


Figure 27. Series 1. Lightning Discharge from the Right Wingtip Probe and Vertical Stabilizer Probe

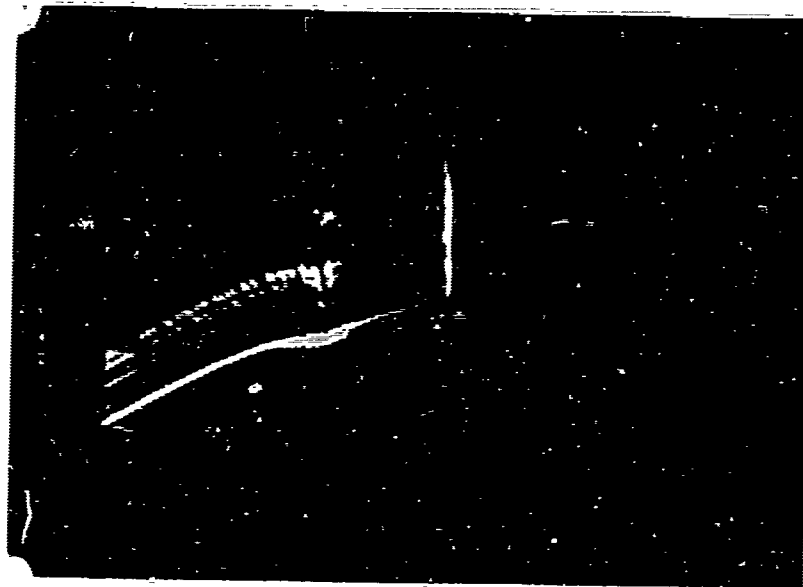


Figure 28. Series 1. Lightning Discharge from the Right Wingtip Probe and Vertical Stabilizer Probe

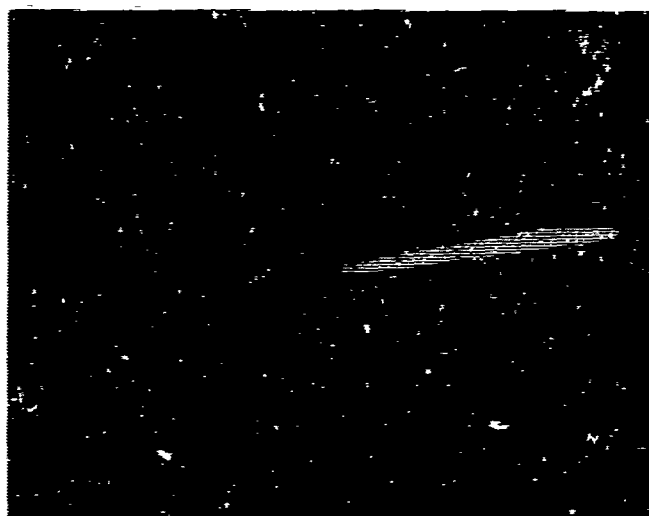


Figure 29. Series 1. Lightning Discharge from the Right Wingtip Probe



Figure 30. Series 3. Segment of a Lightning Strike Surge Channel Below the Noseboom

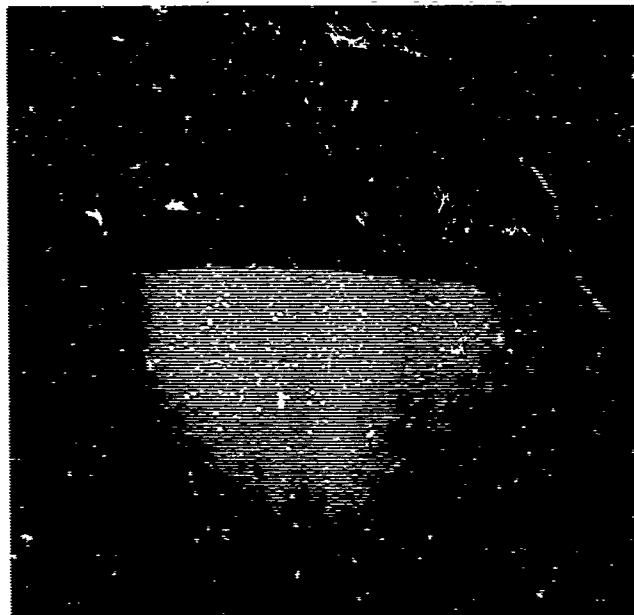


Figure 31. Series 3. Lightning Strike to the Noseboom of the Aircraft and Discharge from the Trailing Edge of the Vertical Stabilizer

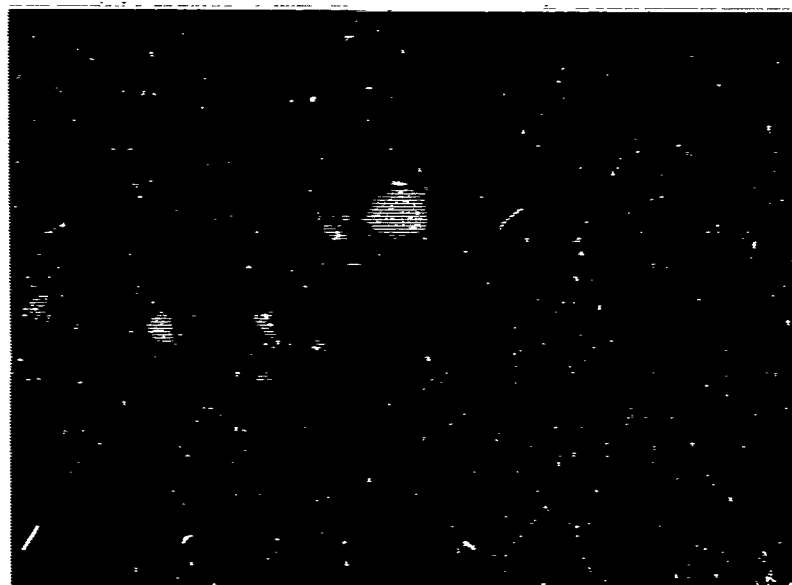


Figure 32. Series 4. Lightning Strike to the Aircraft Noseboom

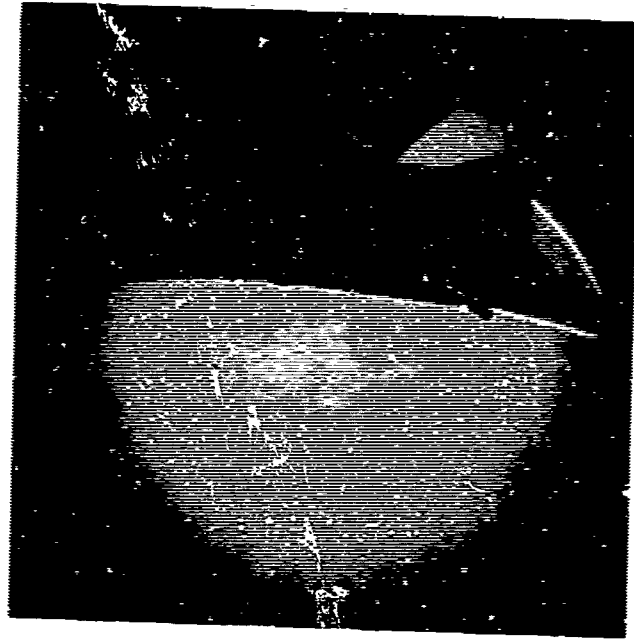


Figure 33. Series 4. Lightning Strike to the Aircraft Noseboom and Corresponding Discharges from the Right Horizontal Stabilizer Diverter-Discharger and from the Trailing Edge of the Vertical Stabilizer

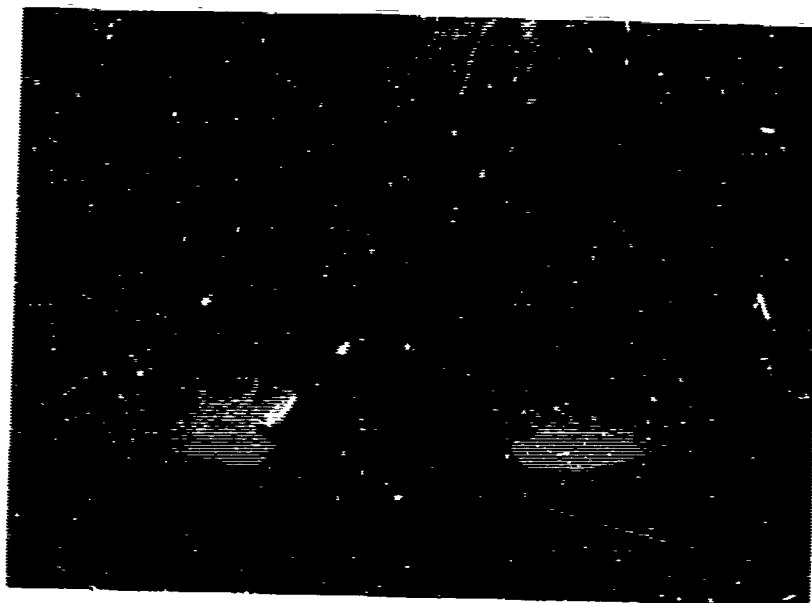


Figure 34. Series 4. Lightning Discharge from the Right Horizontal Stabilizer Diverter-Discharger and a Segment of the Discharge Channel Behind the Aircraft

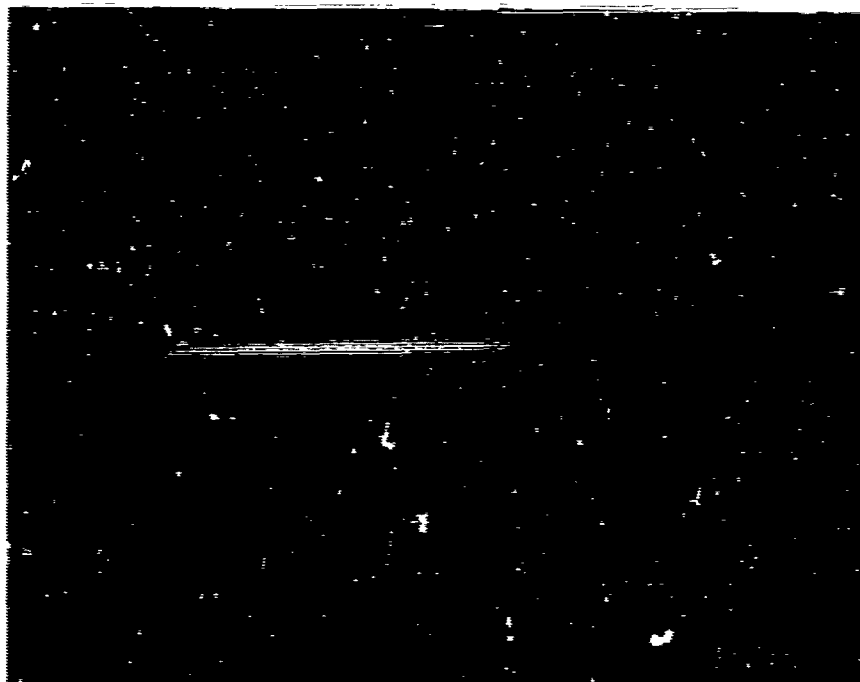


Figure 35. Lightning Burns on the Noseboom

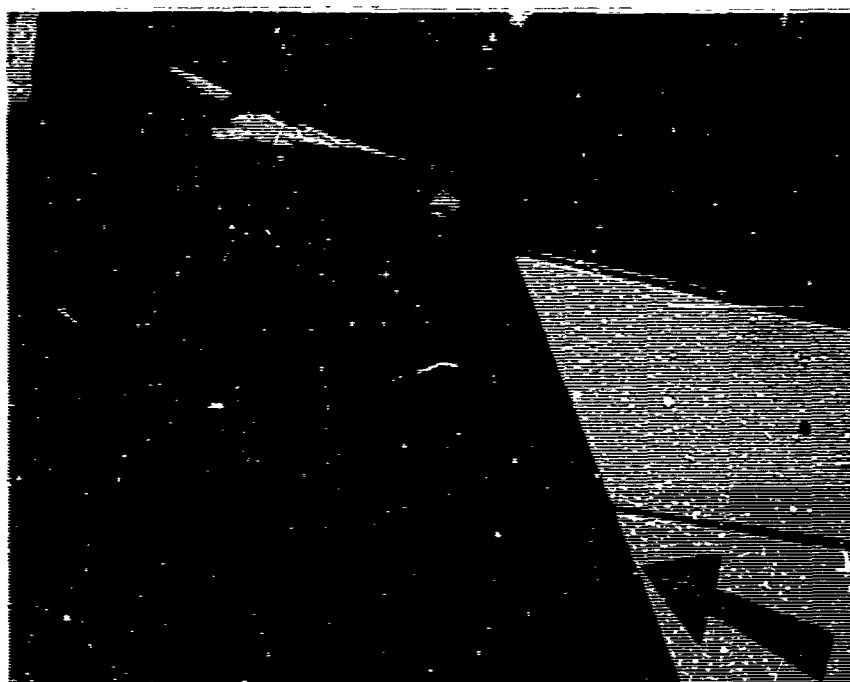


Figure 36. Lightning Discharge Burn on the Trailing Edge of the Rudder
(A few inches from the main fuel vent outlet)

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<p>The ultimate objective of the meteorologists involved in this particular study of the cumulonimbus was to obtain sufficient data during various stages of the cycling thunderstorm so as to be able to produce a detailed model of the subject and thus improve the ability to predict the magnitude and, where applicable, the direction of the variables involved. This project required a platform from which instrumentation could be utilized to sample the sought after storm information. The platform was an instrumented AF F-100F aircraft which was used to penetrate thunderstorms and the air space surrounding the perimeter of the storm. The aircraft was vectored by ground radar into the particular areas of interest to record the various data. This information would be analyzed with data recorded simultaneously by ground based meteorological equipment to provide a relatively detailed, time correlated picture of the synoptic situation. Needless to say, the data acquired is voluminous in quantity and at the time of this writing is in the preliminary stages of analysis. Therefore, this report will not delve into a detailed discussion of the data but shall note from whom such an analysis can eventually be obtained.</p> <p>This abstract has been approved for public release and sale; its distribution is unlimited.</p>		

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